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THE NUMERICAL PREDICTION OF THE DYNAMIC RESPONSE OF A CYLINDRICAL SHELL IN AN ACOUSTIC MEDIUM

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The transient response of an elastic cylindrical shell immersed in an acoustic medium that is engulfed by a plane wave is determined numerically. The method applies the USA-STAGS code which utilizes the finite element method for the structural analysis and The Doubly Asymptotic Approximation (DAA) for the fluid-structure interaction. The calculations are compared to an exact analysis for two separate loadings: a plane step wave and an exponentially decaying plane wave. The results of the comparisons are

within 6% of the exact solution; a fact that supports the applicability of USA-STAGS for fluid-structure interaction problems.

FOREWORD

The transient response of an elastic cylindrical shell immersed in an acoustic medium that is engulfed by a plane wave is determined numerically. The method applies the USA-STAGS code which utilizes the finite element method for the structural analysis and The Doubly Asymptotic Approximation (DAA) for the fluid-structure interaction. The calculations are compared to an exact analysis for two separate loadings: a plane step wave and an exponentially decaying plane wave. The results of the comparisons are most favorable. For the step loading case the agreement is within 3% of the exact solution and for the exponential decaying load case the agreement is within 6%. The success of the comparisons reported herein strongly supports the applicability of USA-STAGS for fluid-structure interaction problems.

D. E. Phillips

D. E. PHILLIPS
By direction

CONTENTS

ILLUSTRATIONS

Chapter 1

INTRODUCTION

Fluid-structure interaction problems have recently been receiving considerable attention in conjunction with efforts to gain a more thorough understanding of the response of submerged structures to underwater shock loading. The difficulty in developing predictive analytical models is twofold. First, the structure must be suitably modeled in order to determine the elastic response. This certainly is within the capability of many structural analysis computer codes. Secondly, the loading effects are altered according to the state of motion of the structure in the fluid. Thus, the problem of determining the loading is one in which the state of motion of the fluid and structure are coupled.

Analytical solutions have been obtained for simple structural geometries with simple temporal and spatial waveforms. However, in some cases even the analytical solutions are conveniently evaluated numerically. In addition, analytical solutions seldom address the problem of internal structure in any detail. In any event, analytical investigations have resulted in the adoption of methods for uncoupling the structure from the fluid.

These procedures, known as surface approximation techniques, have been compared by Geers (Reference 1). It is apparent from his analysis that the Doubly Asymptotic Approximation (DAA) (References 1, 2, and 3) is the most accurate for early and late times in predicting the behavior of submerged shells. The DAA also affords a smooth transition between early and late time response. More recently,

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1. Geers, T. L., "Transient Response Analysis of Submerged Structures," in Finite Element Analysis of Transient Non-Linear Behavior, AMD Vol. 14, ASME, New York, 1975

2. Geers, T. L., "Response of an Elastic Cylindrical Shell to a Transverse Acoustic Shock Wave in a Light Fluid Medium," J. Acoust. Soc. Am., Vol. 48, No. 3, Sep 1970, pp 692-701

3. Geers, T. L., "Excitation of an Elastic Cylindrical Shell by a Transient Acoustic Wave," J. Appl. Mech., Vol. 36, No. 3, Sep 1969, pp 459-469

the DAA has been used in conjunction with several linear elastic finite element computer codes to predict the response of submerged targets to underwater shock loading (References 4 and 5).

Since the close-in underwater detonation of high explosives causes large local plastic deformation, a structural analysis computer code capable of performing such analyses for general shell structures is required. Therefore, NSWC has evaluated the applicability of a broad class of linear and non-linear finite element codes for such analyses. As a result of the evaluation, the STAGS code (Structural Analysis of General Shells) (Reference 6) was chosen because it proved most versatile for performing linear and non-linear analyses of shell type structures.

The STAGS code has been combined with a DAA code, USA (Underwater Shock Analysis) with the resulting code called USA-STAGS (Reference 7). In the following sections we discuss the use of USA-STAGS to predict the response of a linear elastic cylindrical shell immersed in a fluid through which a plane acoustic wave is propagating. The results of the USA-STAGS calculations are compared to an exact analysis by Huang (Reference 8).

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4. DeRuntz, J. A., Geers, T. L., Felippa, C. A., "The Underwater Shock Analysis (USA) Code, A Reference Manual," LMSC-D624328, Contract No. DNA 001-76-C-0285, 28 Feb 1978

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8. Huang, H., "An Exact Analysis of the Transient Interaction of Acoustic Plane Waves with a Cylindrical Elastic Shell," J. Appl. Mech., Vol. 37, No. 4, Dec 1970, pp 1091-1106

Chapter 2

EXACT ANALYSIS METHODOLOGY

Huang's analysis focuses upon the problem of the transient interaction of a plane acoustic wave with a circular cylindrical shell immersed in a fluid. Huang states that "this paper presents an exact formulation by simple transformations of the basic differential equations governing the coefficients of the series solution for the shell deflections and the wave pressure for each 'mode' into a Volterra integral equation of the second kind." The kernel is constructed on the basis of a special function which has been tabulated by Nielsen for the application in supersonic interference problems. The integral equations are then solved by a step-by-step integration scheme. This method is also very efficient for parametric studies, and the entire computation process is quite straightforward, and can easily be controlled to have a high degree of accuracy.

Exact series solutions are presented in this work for the case of a neutrally buoyant steel shell submerged in water subjected to step and exponentially decaying incident waves. The complete pictures of the total motion and stress responses of the shell are revealed. The material properties used were those of steel for the shell and water for the fluid. The case which was chosen to model on USA-STAGS involved a thickness to radius ratio equal to 0.065.

In the derivation of the shell equations, the relative changes in length and shear of the shell middle surface and the change of curvature and twist have been accounted for as in Junger (Reference 9). Thus, the shell equations used are quite general and are exact for the elastic behavior of the shell within the Kirchoff assumptions in shell theory (Reference 10).

Consider a linear elastic cylindrical shell with a modulus of elasticity, E, Poissons ratio, ν, and density, ρ_s, immersed in an infinite acoustic media having density, ρ, and sound speed, c. The geometry of the problem is given in Figure 1.

Huang has chosen to give his exact solution in non-dimensional form. His exact solutions for both the step and exponential loadings are given in Figure 2 where $\dot{\underset{\sim}{w}}(0,t)$ represents the radial velocity at $\theta = 0^o$, the leading edge of the shell as a function of time. The velocities have been non-dimensionalized by $\Omega = P_0/\rho c$. The time has been non-dimensionalized by c/a which represents the time required for the acoustic wave to transit the radius of the shell. In the subsequent sections we plot our results in a like manner.

9. Junger, M. C., "Vibrations of Elastic Shells in a Fluid Medium and the Associated Radiation of Sound," J. Appl. Mech., Vol. 19, Trans. ASME, Vol. 74, 1952, pp 435-439

10. Novozhilov, V. V., Thin Shell Theory, translated by Lowe, P. G., and edited by Radok, J. R. M., P. Noerdhoff Ltd., Gröniger, the Netherlands, 2nd Revised Edition, Chapter 1, 1964

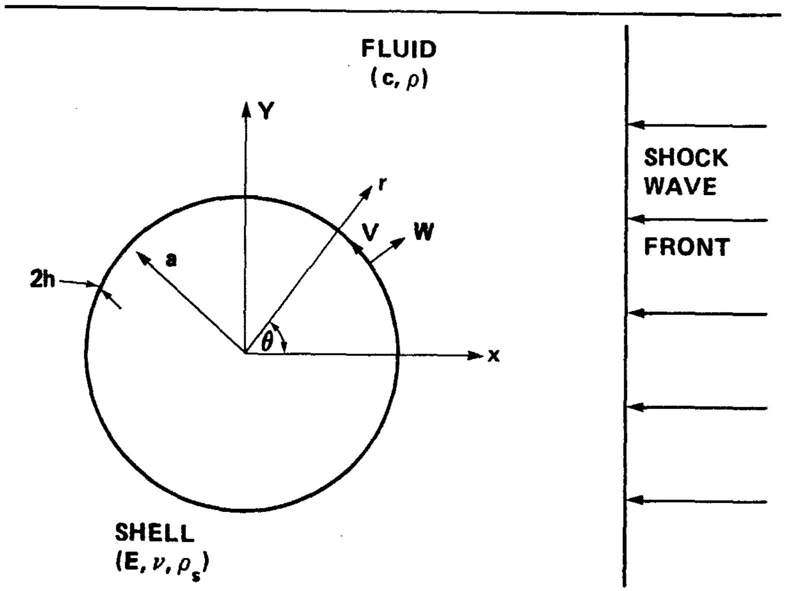

FIGURE 1. GEOMETRY OF PROBLEM.

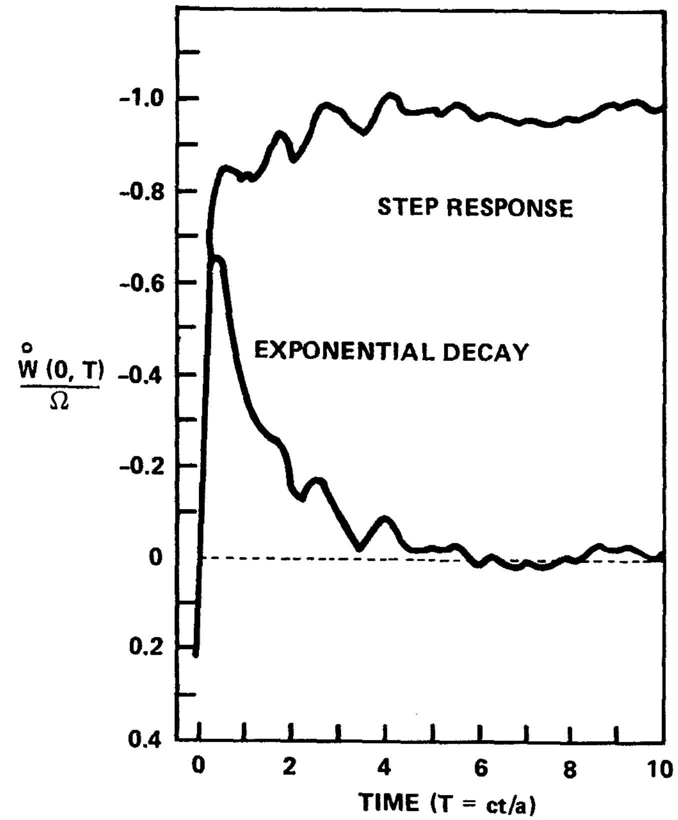

FIGURE 2. HUANG'S DIMENSIONLESS RESULTS FOR h/a = 1/31.

Chapter 3

USA-STAGS ANALYSIS PROCEDURE

The USA-STAGS code makes use of the finite element method for the structural response and the DAA for the fluid-structure interaction. The coupled system of equations is

$$\underset{\sim}{M}\,\ddot{\underline{x}} + \underset{\sim}{K}\,\underline{x} = -\,\underset{\sim}{T}\,\underset{\sim}{A}\,(\underline{P}_S + P_I) \tag{1}$$

$$\underset{\sim}{A}\,\dot{\underline{P}}_S + \rho\, c\, \underset{\sim}{A}\,\underset{\sim}{M}_F^{-1}\underset{\sim}{A}\,\underline{P}_S = \rho\, c\, \underset{\sim}{A}\,(\underset{\sim}{T}^T\,\ddot{\underline{x}} - \ddot{x}_I) \tag{2}$$

Variables appearing here are defined as:

$\underset{\sim}{M}$	Structural mass matrix
$\underset{\sim}{K}$	Linear or non-linear structural stiffness operator
$\underline{x}$	Structural displacement vector
$\ddot{\underline{x}}$	Acceleration vector
$\underset{\sim}{T}$	A transformation matrix (rectangular) which relates displacement variables in fluid to those in structure
$\underset{\sim}{A}$	Fluid element area matrix (diagonal)
$\underline{P}_S$	Vector representing scattered fluid pressure
P_I	Vector representing incident fluid pressure
$\underset{\sim}{M}_F$	Fluid mass matrix
ρ	Fluid density
c	Speed of sound in fluid
$\ddot{\underline{x}}_I$	Vector of fluid particle acceleration due to the incident wave.

Step-by-step integration is carried out with a staggered solution procedure described below

(1) estimate $\underline{\ddot{x}}$ at next step by extrapolation of previous value

(2) solve (2) for $\underset{\sim}{P}_S$

(3) solve (1) for $\underline{x}$

This solution procedure is conditionally stable. Consequently, the fluid equation (2) has been altered to achieve unconditional stability (Reference 11).

In order to predict the transient response of a cylindrical shell immersed in a fluid excited by an acoustic wave, a finite element model of the cylinder has been constructed. Since the plane strain response of the cylinder is desired, a finite element model of arbitrary length may be used. In fact, a finite element model consisting of one element along the length is adequate.

Two finite element models have been used for the analysis. The first model has a length to diameter ratio of 10. A model of that size has been used so that the added mass effects (described by $\underset{\sim}{M}_F$ in equation (2)) can be properly described. The second is a ring model having unit length. The added mass for the model is described by using additional boundary elements (Reference 12).

---

11. Park, K. C., Felippa, C. A., DeRuntz, J. A., "Stabilization of Staggered Solution Procedures for Fluid-Structure Interaction Analysis," pp 95-124 in Computational Methods for Fluid Structure Interaction Problems, AMD--Vol. 26, ASME, New York, 1977

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Chapter 4

RESULTS AND DISCUSSION

Two analyses have been performed with USA-STAGS and the results have been compared to the exact analyses of Huang. The first concerns the step pressure wave shown in Figure 3a, and the second the exponentially decaying pressure wave shown in Figure 3b. The standoff distance from front of the cylindrical shell to the point of source is 100 diameters. For this standoff, the wave impinging on the target is nearly planar.

4.1 FINITE LENGTH MODEL

The integration procedure used for the staggered solution is the Park's linear multi-step method (Reference 13). Since the integration procedure for the coupled equations is unconditionally stable, a time step is chosen to achieve accuracy in the solution. A time step of about 1/50 of a transit time has been used for all analyses. (The transit time is the time required for the acoustic wave to traverse the shell.)

The result of the USA-STAGS calculations are compared to the exact analyses in Figures 4 and 5. Figure 4 gives the non-dimensional velocity response of the shell at the horizontal centerline for the step wave loading. (The velocity has been non-dimensionalized as $\overset{o}{W}/\Omega$, where $\Omega = P_0/\rho c$.) The calculations compare very well with the exact analyses for the 3.75 transit times shown. The USA-STAGS results show good agreement for both frequency and amplitude.

The non-dimensional velocity response comparisons for the exponential wave are shown in Figure 5. USA-STAGS results tend to oscillate more than the exact analysis. This can be accounted for by the observation that the exact solution contains contributions from the first seven modes. The USA-STAGS calculations contain contributions from higher modes. These higher modes are excited by the rapidly decaying incident pressure wave (the duration of the loading is 0.06 transit times).

4.2 RING MODEL

Even though the previous finite length model gave satisfactory results, the plane strain response can be simulated with a model of arbitrary length. Therefore, a finite element model consisting of one element in the axial direction

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13. Park, K. C., "An Improved Stiffly Stable Method for Direct Integration of Non-Linear Structural Dynamics," J. Appl. Mech., Vol. 42, 1975, pp 464-470

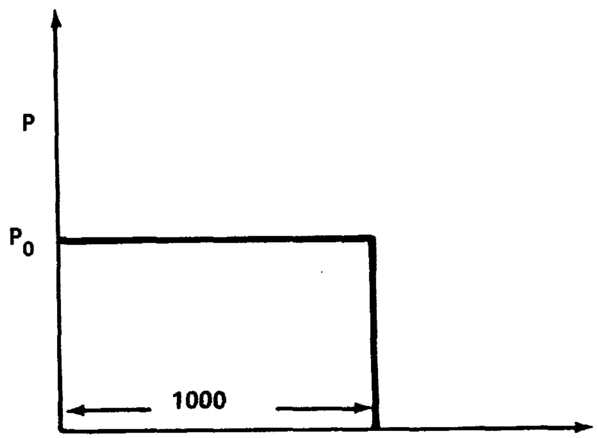

FIGURE 3a. STEP WAVE PRESSURE.

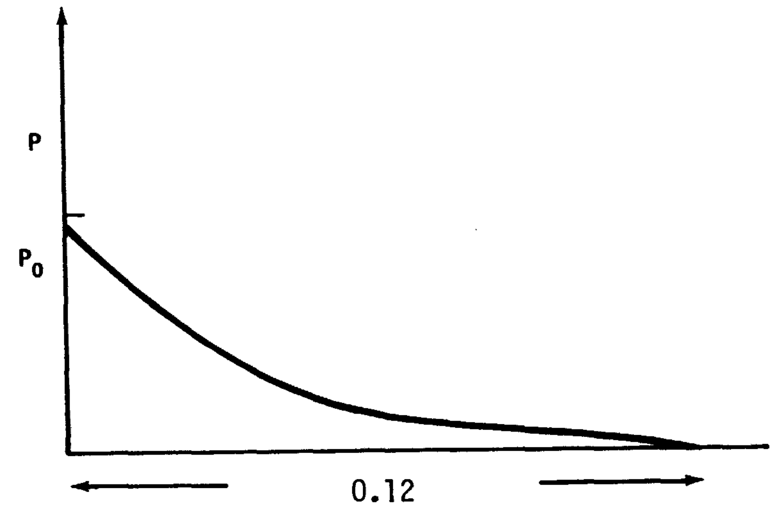

FIGURE 3b. EXPONENTIAL WAVE PRESSURE.

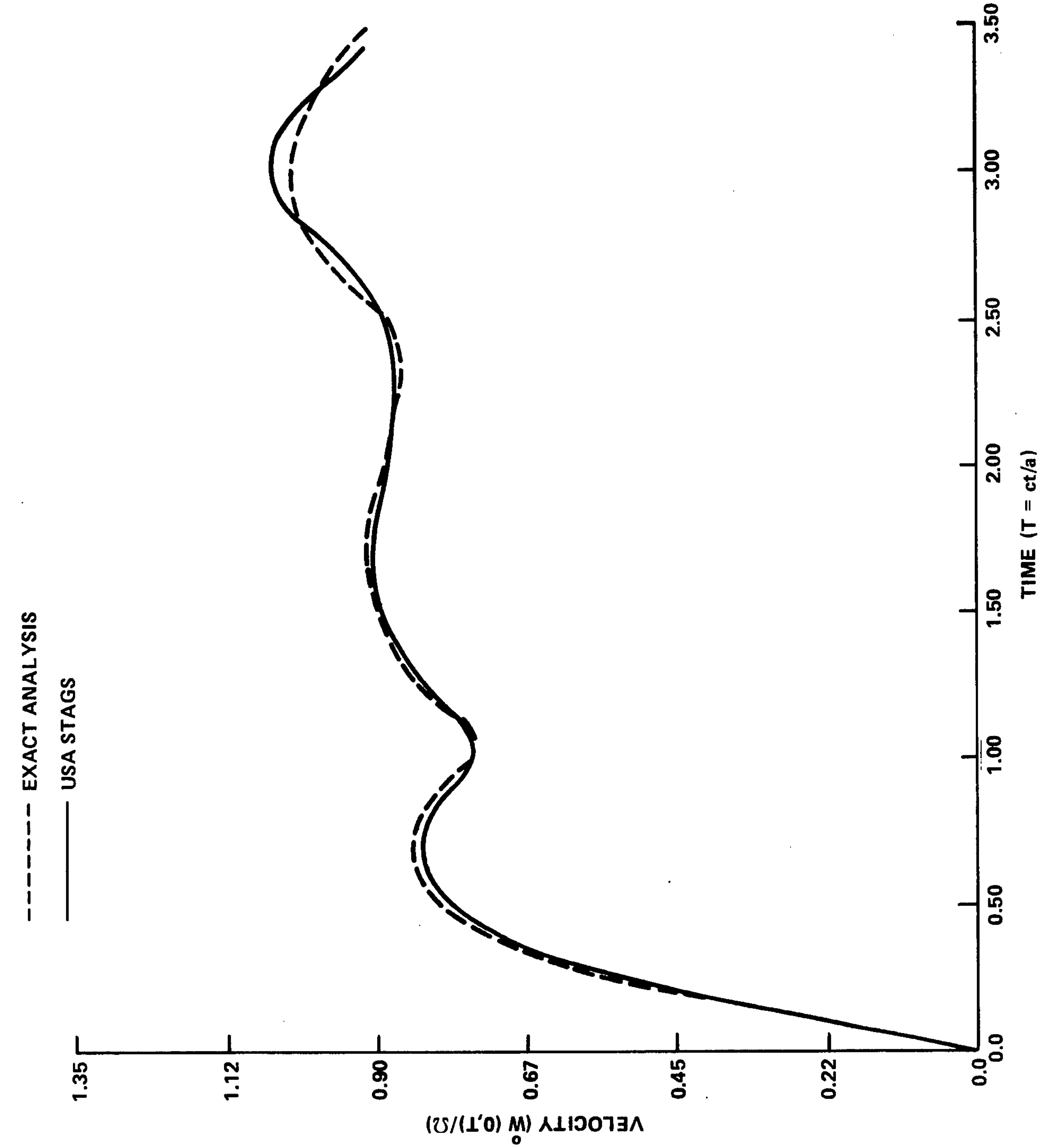

FIGURE 4. VELOCITY COMPARISONS FOR STEP WAVE.

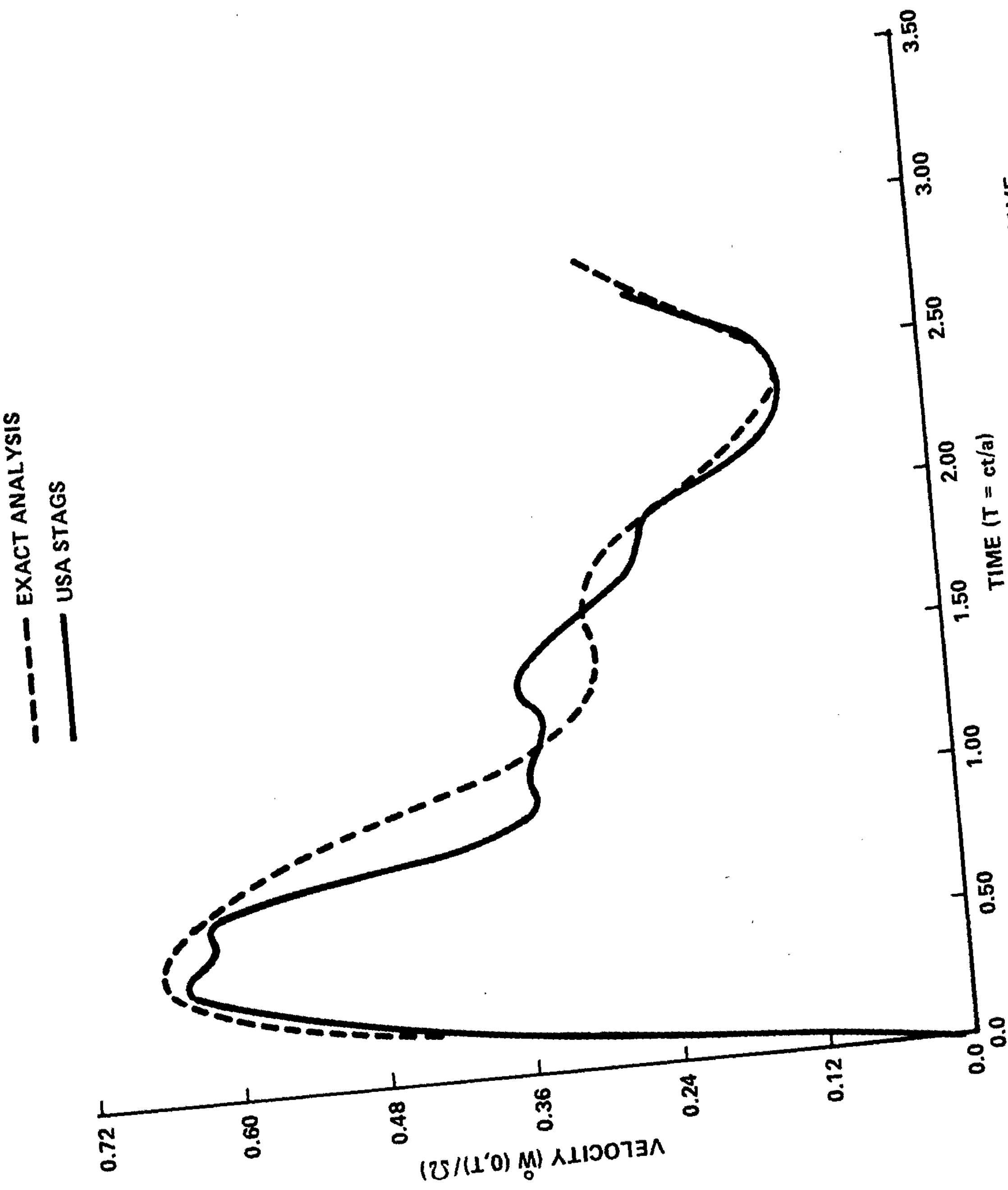

FIGURE 5. VELOCITY COMPARISONS FOR EXPONENTIAL WAVE.

has been constructed (Figure 6). Since USA-STAGS uses boundary integral techniques to determine the added mass, additional boundary elements have been introduced to describe the plane strain response.

The results of the USA-STAGS analysis are shown in Figure 7 and Figure 8. Figure 7 gives the velocity response of the horizontal centerline under the step wave loading. The agreement between the exact analysis and the USA-STAGS analysis is quite good for the time shown. For the mid-time region (between 2.4 and 5.0 transits) the amplitudes of the numerical results are somewhat higher and they contain more oscillation. For the later time response (greater than 5 transits) the oscillations in the numerical results are annihilated by the radiation damping.

The velocity response of the horizontal centerline for the exponentially decaying loading is shown in Figure 8. The agreement between the exact solution and the numerical results is quite close. The agreement for the peak amplitude is very favorable although the numerical results contain a few more oscillations.

4.3 LATE TIME ASYMPTOTE

Another measure of the accuracy of the numerical method is the late time asymptote. Huang indicates that the theoretical late time asymptote for the geometry under consideration is unity (in terms of non-dimensional velocity) for the step wave loading. The "plane wave" approximation of Mindlin and Bleich (Reference 14) also gives an asymptotic value of unity. In addition, the "cylindrical wave" approximation of Haywood (Reference 15) gives a late time asymptote of unity.

The late time asymptote is shown in Figure 7. The USA-STAGS results approaches the late time asymptote quite rapidly. In fact, after 6 transits the numerical results are within 5% of the asymptotic value. After 20 transits the numerical results are within 2% of the late time asymptote.

For the case of the exponentially decaying loading, the late time asymptote is zero. The USA-STAGS analysis approaches the asymptotic value rapidly after 4 transits; the numerical results are within 7% of the asymptote value. Again after 20 transits, the numerical results are within 1% of the late time asymptote.

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14. Mindlin, R. D., Bleich, H. H., "Response of an Elastic Cylindrical Shell to a Transverse Step Shock Wave," J. Appl. Mech., Vol. 20, Trans. ASME, Vol. 75, 1953, pp 189-195

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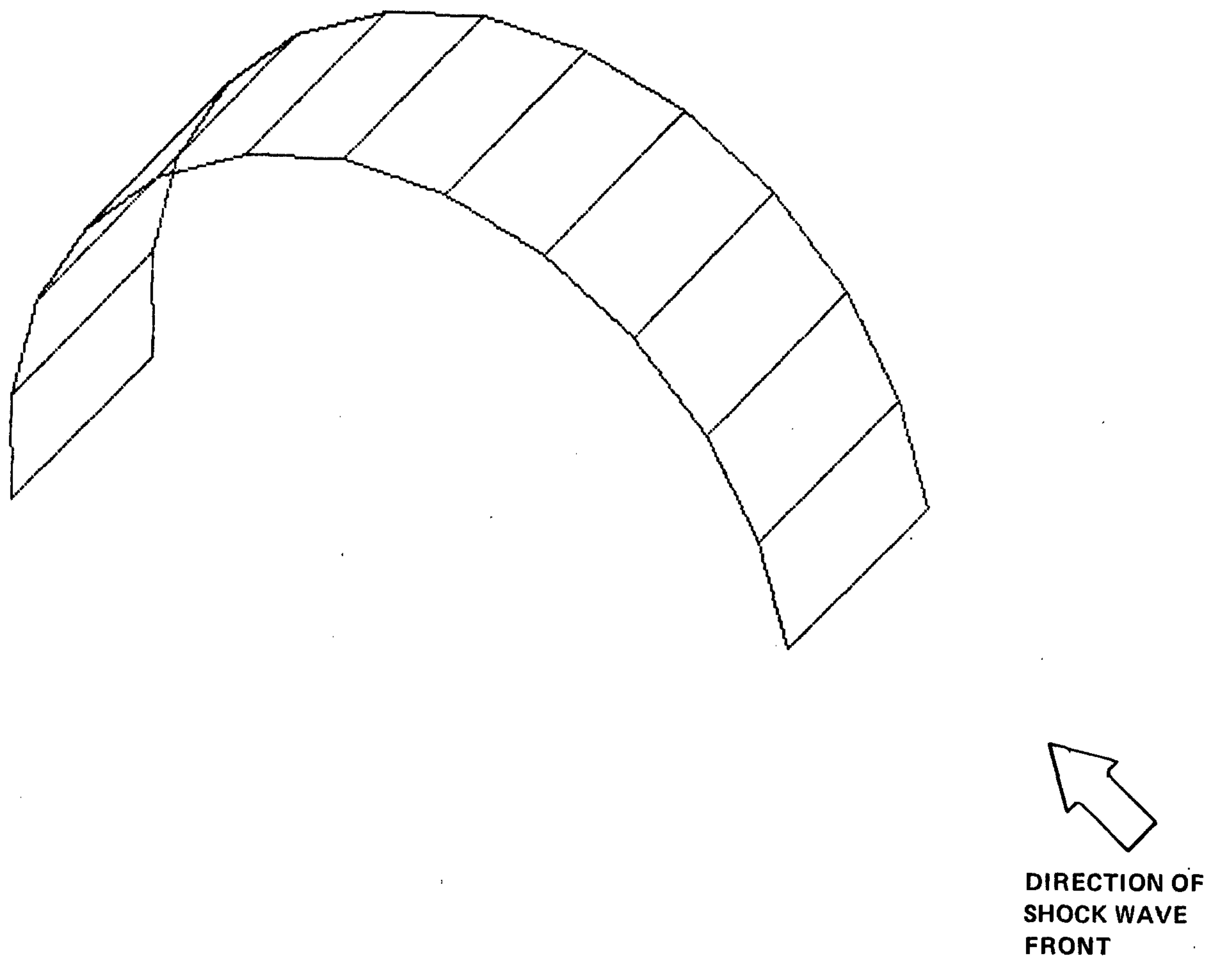

FIGURE 6. PLANE STRAIN FINITE ELEMENT MODEL.

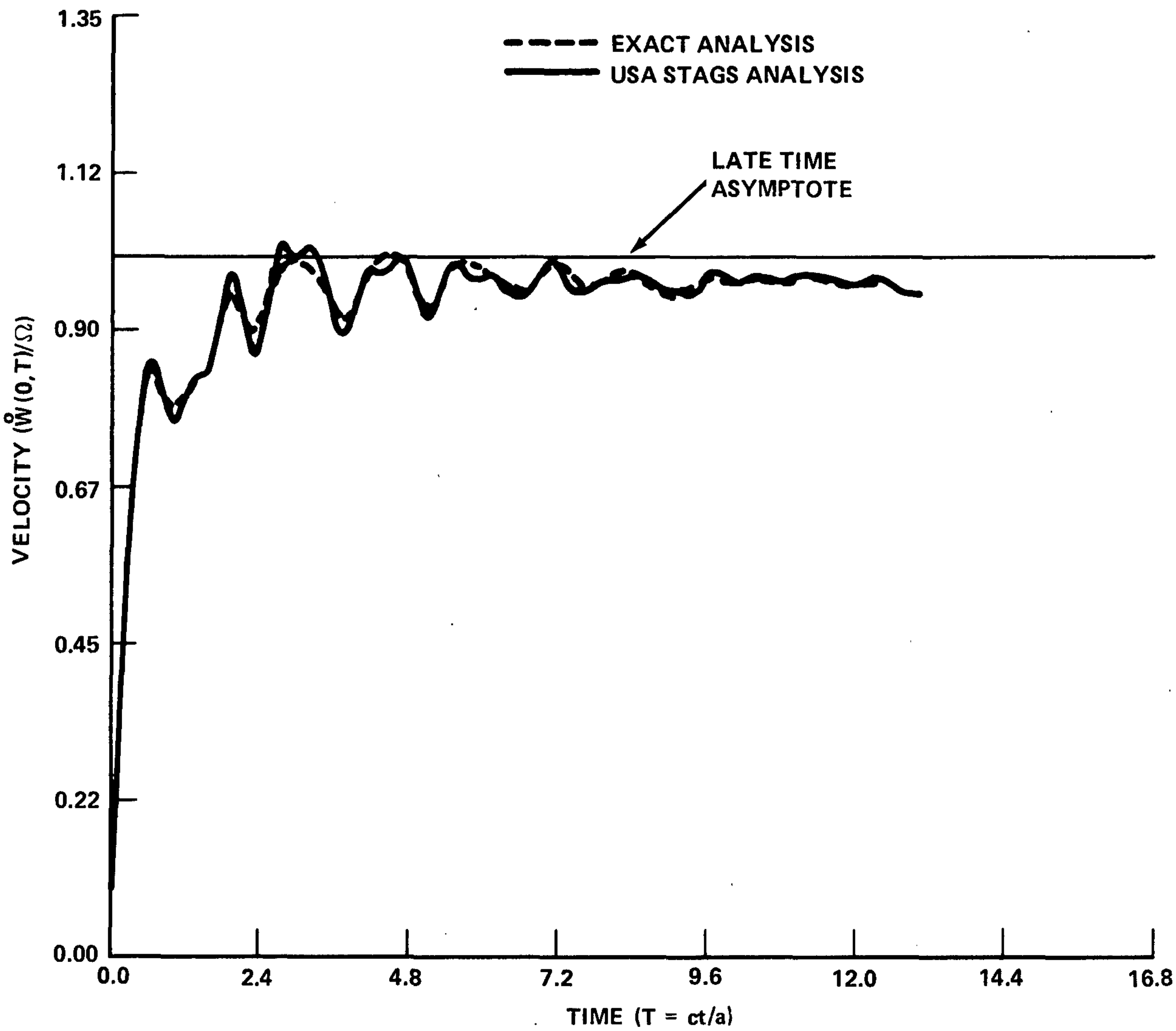

FIGURE 7. VELOCITY RESPONSE FOR STEP WAVE LOADING.

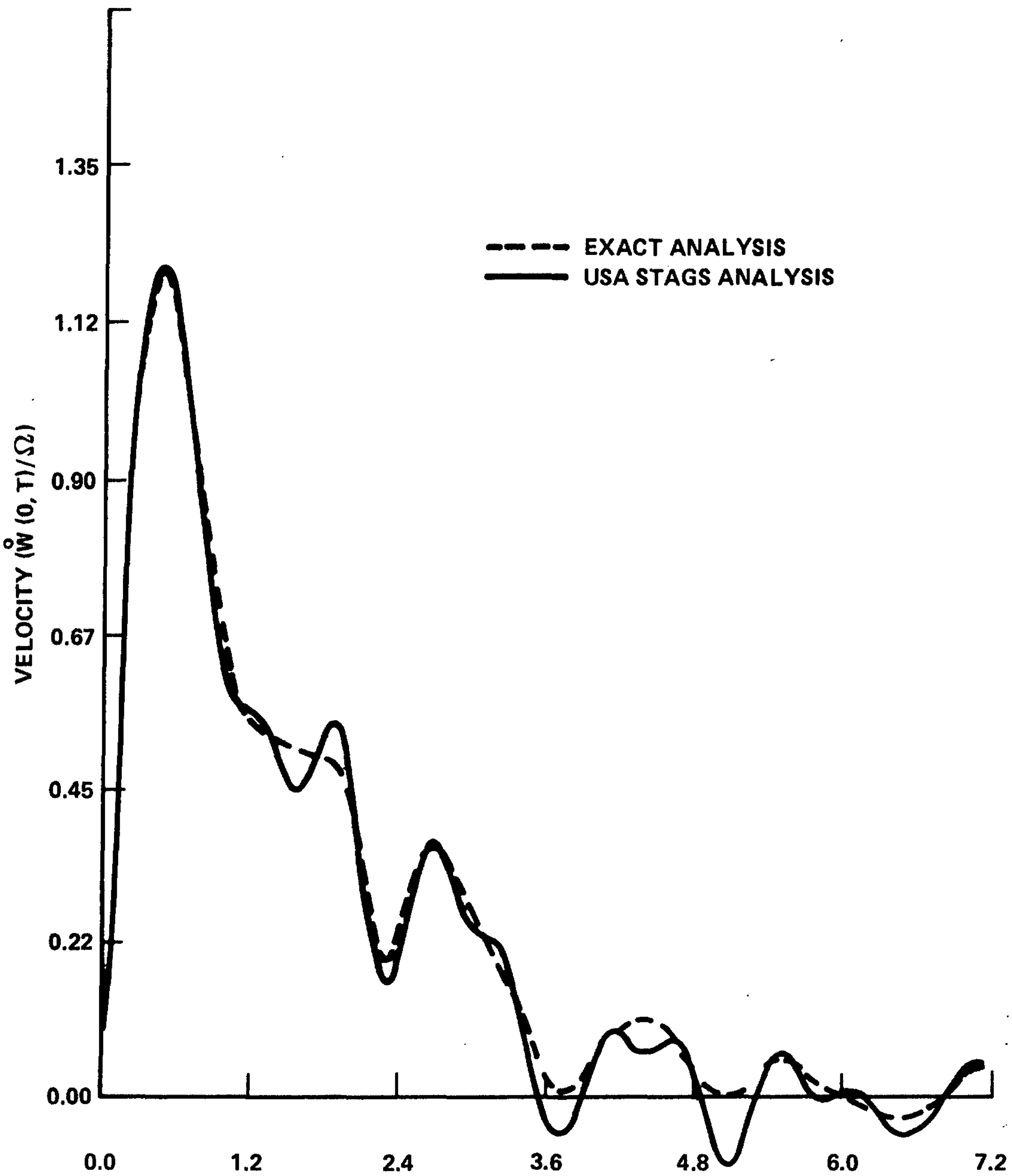

FIGURE 8. VELOCITY RESPONSE FOR EXPONENTIAL DECAYING LOAD.

Chapter 5

CONCLUSION

For plane shock wave loading, a comparison of an exact solution for the velocity response of a cylindrical shell immersed in a fluid with that of a solution generated by a fluid analyzer and structural code (USA-STAGS) has been presented. Good agreement has been obtained for step and exponential pressure wave loading. In addition, the USA-STAGS predictions compare favorably with the late time asymptote.

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TERMS

a	radius
c	sound speed in fluid
h	half the thickness of the shell
t	time
E	modulus to elasticity
P_o	peak incident pressure ($T = c\varepsilon/a$)
T	non-dimensional time
W	radial displacement of shell
$\dot{W}$	radial velocity of shell
Y	circumferential displacement of shell
ρ	density of fluid
ρ_s	density of shell
ν	Poissons ratio
Ω	strength parameter ($\Omega = P_o/\rho c$)

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